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HISTORY OF THE R-4360

Circumstances Surrounding Initial Studies of the R-4360 Engine

For a number of years, Pratt and Whitney Aircraft experimented with various types of liquid-cooled aircraft engines varying from Diesel or gasoline to sleeve valve or poppet valve arrangements. In the period through 1938 to 1940, efforts were directed primarily to the development of two sizes of 24-cylinder liquid-cooled sleeve valve "H" type engines, one of 2600 cubic inch displacement known as the H-3730 Series. Several innovations in method of injecting the fuel brought about by integral multi-stage supercharging and intercooling created many unusual and difficult problems in the induction and carburetion systems of these engines. Similarly, problems were introduced in the design and manufacture of durable sleeve valves, reduction gears, and crankcases that are not inherent with radial air-cooled engines, and with which the majority of personnel at Pratt and Whitney Aircraft had little or no experience. For these reasons, and undoubtedly many more, plus the fact that a war seemed imminent, it was felt that by reverting to designs with which we were familiar and also a design which was readily adaptable to our tools and manufacturing procedure, we could do a much better job in favor of a 28-cylinder air-cooled four-row radial engine. Therefore, it was decided (with the consent of both Army and Navy) to abandon development of these engines.

Historical Dates of the R-4360

1. Design work was authorized by the Management, November 11, 1940.

2. The first engine, made up largely of salvaged 3130 reduction gear, R-2180 rods, R-2800 front bank cylinders and R-2800 rear, a cast steel crankshaft and hurriedly manufactured crankcases, ran on April 28, 1941. Figure 24.

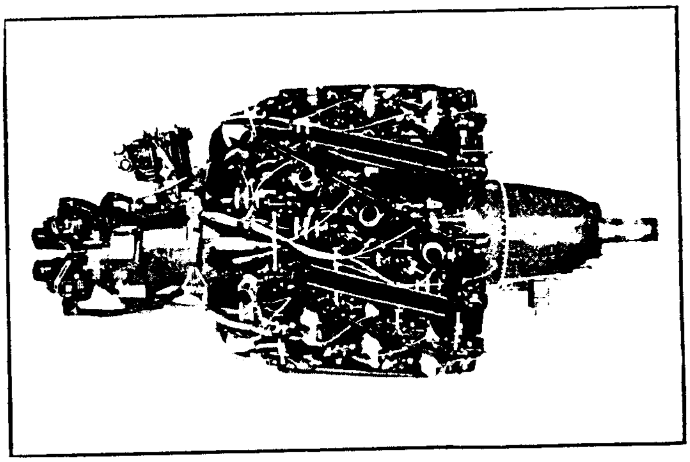

Figure 24 - The First R-4360 Prototype Engine

3. During 1941, three four-row engines and one single-row engine had been run and parts for six engines had been fairly well machined. At the end of 1941, approximately 1 year after starting design, 500 hours of full scale operation plus 176 hours of single-row operation and 1412 hours of single-cylinder operation had been completed.

4. The first flight of the R-4360 was made on May 25, 1942, on the third R-4360 engine. This flight was made in a converted Vultee Vengeance known as the V-85. Unfortunately, this airplane was wrecked late in 1942 in a forced landing in a tobacco field north of Hartford. The forced landing

was caused by a ruptured fuel nozzle diaphragm combined with a plugged nozzle vent passage resulting in cutting off the fuel supply in the engine. Fortunately, at that time, and to this date, no serious injuries have been inflicted upon any personnel flying behind an R-4360 that has been attributed to the engine. There have been two serious accidents, one involving Howard Hughes and the second is the mid-air collision of two Navy craft.

5. During 1942, the engine was released to Semi-Production and in 1943, ten engines were delivered as experimental models for prototype aircraft.

6. The original R-4360 as shown by Figure 24 was made with R-2800 front bank cylinders. The fourth engine was the first to operate with forged heads. However, the intake pipes were located in the position now occupied by the exhaust. This was the only engine operated in this manner, it being found more efficient from a performance standpoint to operate with a top intake and side exhaust. This method also allowed a very simple manifolding system to be used on both pusher and tractor engines without any other change to the cylinder being made other than to reverse it 180 degrees on the crankcase.

7. In the final designs of the R-4360, it was possible to take any power section and convert it to a tractor or pusher model by changing only the cams, reversing the cylinders and changing the intake pipes and baffles. This same basic power section was used on all the multiplicity of models designed around the R-4360. A similar application was made to the rear section where converting from single to auxiliary stage involves little more than the removing of a rear cover plate and substituting the additional stages of parts, or a single-stage, single-speed rear section could be converted to a single-stage variable-speed rear with a simple addition of parts. Similar applications were present, although to a lesser degree, in converting from single to dual rotation reduction gear. The object of this was to manufacture an engine that could be easily converted to any number of models without having to have a great number of different machine operations for each, with a consequent reduction in costs, machining space and equipment. A review of the large number of models which have been put out would indicate the need for this procedure.

8. At this date, 21,805 hours of multi-cylinder testing, 1980 hours of single-row testing and 34,720 hours of single cylinder testing have been accumulated. Specifications have been made and engines built conforming to 33 different models, each one adapted to a particular airplane installation or installations. At this time, Experimental operates a total of 26 R-4360 multi-cylinder engines for purposes of development, model and type best, performance, and flight test. The culmination of this development work is the present R-4360-B Series engine now in production. (Figure 25).

AIRPLANES USING R-4360 ENGINES

In order to understand why so many models of engines were designed, it is necessary to review the different types of airplanes for which they were intended.

The following is a list of the airplanes in the order in which they flew with some pertinent notes with regards each:

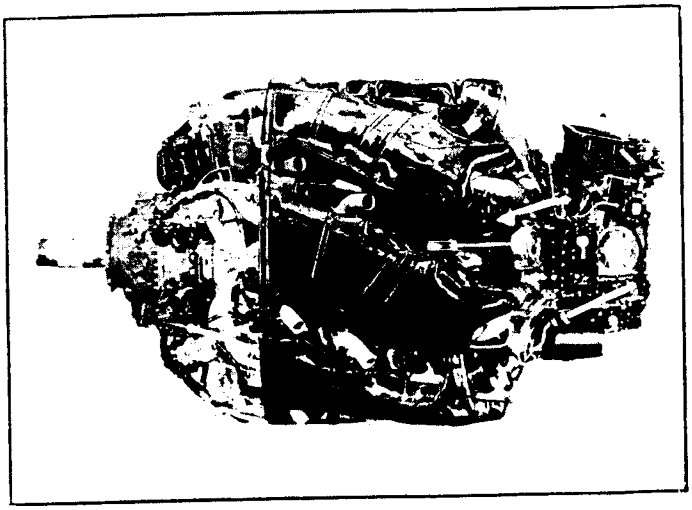

Figure 25

1. Vultee Model 85 - A Pratt & Whitney experimental test ship sponsored by the Army Air Corps for testing single-stage R-4360 engines.

2. Vought V-326 high altitude test ship for testing multi-stage or turbo applications of the R-4360. Two of these airplanes were built.

3. Republic XP-72 used the R-4360-19. Its predominant feature was a remote-mounted, engine driven auxiliary stage supercharger. In this particular airplane the pilot was positioned between the engine and the auxiliary stage. Both dual rotation and single rotation propellers were tested on this airplane.

4. Vultee XA-41 - R-4360-9. This was primarily a low level attack ship carrying either a torpedo or bomb load and using a two-speed single stage supercharged engine. This airplane is currently being used by Pratt & Whitney Aircraft for experimental flight test activities.

5. Goodyear XF2G-1 using the R-4360-4. A single-stage variable-speed rear engine. The first airplane of this type was a converted F4UM constructed by the Installation Department of Pratt and Whitney Aircraft on a Navy loaned F4U Vought airplane. The final F2G sported several improvements such as bubble canopy, greatly improved stability characteristics, particularly upon landing, and a trick tab arrangement for counteracting propeller torque under carrier wave-off conditions. During the testing of this airplane it was never felt that a dual rotation reduction gear was necessary to help torque characteristics with the possible exception of carrier wave-off, a problem which was very cleverly overcome by Goodyear Aircraft. This airplane had a terrifically high rate and high angle of climb and for this reason this airplane was used to develop the engine scavenge system, more details of which will be discussed later.

6. Martin AM-1 (Mauler) used the R-4360-4 engine.

7. Boeing XF8B-1 fighter used the R-4360-10 two-stage engine and also a dual rotation reduction gear.

8. Curtiss-Wright XBTC-2 using the R-4360-14.

9. Douglas XTB2D-1 used the R-4360-8.

10. Boeing B-50, C-97 and 377 prototype, the XB-44. R-4360-33 two-stage engines were used in the XB-44 and the -35, which is a single-stage turbo type engine, is intended to be used on the B-50 and the 377. B-44 was

loaned to Pratt and Whitney by the Army and the four R-4360's installed under Army contract through joint cooperation between the Army, Boeing and Pratt and Whitney Aircraft personnel. As a result of tests on this airplane, it was decided before the end of the war with Japan to get this airplane into mass production just as fast as possible. At the present time, a large proportion of our post-war business is centered around the B-50, the C-97 cargo ship, and the 377 Boeing commercial stratacruiser.

11. Douglas C-74 uses R-4360-27 engines similar to the Navy -4 with the exception of the reduction gear. A medium number of these airplanes are being built and several of them have been delivered.

12. Republic XF12 or Rainbow - This airplane will eventually use the R-4360-35. It now uses the -37.

13. Northrop XB-35 ship uses the R-4360-17 and -21 engines, their only difference being in the length of the extension shaft. This is perhaps the most unusual engine model Pratt and Whitney Aircraft has ever built and has required a more extensive outlay for testing facilities than any other engine. Originally, this engine had been scheduled to use a two-speed dual rotation reduction gear. However, this was abandoned because of its extreme complexities and weight. This engine has a turbo-type rear and a two-speed fan drive, also equipped with a fan brake.

14. Martin Mars uses the R-4360-4. At the present time, one of these airplanes has been flown equipped with R-4360's.

15. Hughes F-11 - One of two of these airplanes was lost on its first flight. The plane uses R-4360-31 engines, featuring dual rotation reduction gear.

16. The most recent airplane to fly has been the giant Consolidated Vultee XB-36 equipped with six R-4360-25 pusher engines. These engines, like the XB-35 engines, are equipped with a fan drive and power take-off. At the present time, 100 of these airplanes are scheduled to be built.

17. Hughes H-4 eight-engine flying boat. This project uses R-4360-4A engines and originally started out as the brain child of Henry Kaiser, who is no longer associated with this project.

18. Lockheed XR-60, more commonly referred to as the Lockheed Constitution, uses the R-4360-18 engine. Two of these airplanes are being built for the Navy, one of which has been flown.

19. Aero Sudest (French) four-engine airliner. This will use a model similar to the R-4360-20W. The original four "Power Pack" nacelles are being engineered by Pratt and Whitney Installation Engineering.

20. Martin XP4M-1 - Uses two R-4360-4 engines plus two GE jet engines. It has been flown.

Of general interest are the following airlines scheduled to use R-4360 engines:

Airlines

Pan American World Airlines	20 - Boeing 377 Stratacruisers
Northwest Airlines	10 - Stratacruisers
American Overseas Airlines	8 - Stratacruisers
United Airlines	7 - Stratacruisers
British Overseas Airways	6 - Stratacruisers
A.B.A. (Swedish)	2 - Stratacruisers
D.D.L. (Danish)	1 - Stratacruiser
D.N.L. (Norwegian)	1 - Stratacruiser
Air France	Aero-Sudest

PROBLEMS ENCOUNTERED IN THE DEVELOPMENT OF THE R-4360 ENGINE PECULIAR ONLY TO THAT ENGINE

In the course of the development of a new engine, the ratings at which initial development is started are usually at the current BMEP rating of the most recent production model of the next largest size engine. In the case of the R-4360, the initial development centered around ratings similar to that of the R-2800-B. Usually, before very many years have progressed, engine ratings generally exceed those of previous engine models such as the R-2800 exceeds that of the R-1830. This is generally caused by inability to stay within dimensional limitations for installation or service replacement requirements and it becomes necessary to introduce an entirely new engine. This point is only now being reached in the R-4360 engine where we are going from an R-4360-B Series to the R-4360-C Series. The "A" Series R-4360 never materialized much beyond the thinking stage as it was found in the early development that the engine was capable of 3000hp ratings instead of the original 2800 hp "A" rating. It does appear at this time that the current 3500 hp rating for take-off on the "B" engine will be about as high as we will go although war emergency ratings are probably possible up to 4400 hp or higher.

About a year and one-half ago, an R-4360 engine was operated in excess of 4400 hp for three days of demonstration and accumulated approximately 22 hours of operation in this range. This same engine was also calibrated and run for about an hour as high as 4850 and, subsequently, was run for 100 hours at 3000 hp and approximately 50 hours at 3500hp before disassembly. This engine was still in serviceable condition at this time. This engine was drawn from Production at that time and was not in any way similar to the more fully developed R-4360-35 now in Production.

In the course of developing the R-4360, those problems common to other engine models and currently being investigated by the other engine groups, were very often sidetracked and the efforts of the R-4360 Group concentrated entirely on the features peculiar only to the R-4360. As an example of this is the case of the piston and ring assembly where at elevated powers, both in the R-2800 and R-4360, ring sticking has been a constant source of annoyance. In this case, the R-4360 Group suffered along by overcooling or babying the piston assemblies through endurance and the R-2800 Group carried on the development of a piston and ring assembly that would be free of sticking. At the conclusion of their investigation, the piston and ring assembly adopted in the R-2800 was used in the R-4360. This is possible to do in most cases but very often cases arise where items used satisfactorily on other engines cannot be used on the R-4360.

On R-2800's, hose clamps and connections have proved quite satisfactory on the rocker drain system, however, the oil temperatures in the rocker drain system on the R-4360 are considerably higher than in the R-2800, which resulted in severe deterioration of the rocker drain hoses after a relatively few number of hours. It was, therefore, necessary to develop a rocker drain system using a more heat-resistant material. This has been very satisfactorily done by the use of the new silicone rubbers. Silicone, however, has an unusual property of flowing readily and it, therefore, had to be completely confined. Any flow characteristics of this rubber are absorbed by a spring-loaded follow-up which eliminates the necessity of servicing these parts during engine operation.

The following items are some of the more interesting and complex problems which were encountered during the development of the R-4360 and for the most part are peculiar to that type of engine. At some time or other, almost every part of the engine will require some improvement or design change and parts that initially were free from trouble will become troublesome as the engine is further developed and we are able to accrue more and more time at elevated powers. Probably the most interesting part of engine development is the constant possibility that anything from a cotter pin to a crankshaft may be the next item to get in trouble as the power conditions are elevated and in probably 75% of the cases it is impossible to predict which one it will be.

CRANKSHAFT

As sometimes happens, although quite unusual, the crankshaft lost weight during its initial development. In some experimental testing in over-speed conditions (not a condition encountered for any appreciable time in service) it was possible, after 50 hours of operation at this condition to develop cracks at the crank cheek. This condition was traced to stiffness in this portion of the crankshaft which, because of the flexibility of other portions of the shaft, resulted in stress concentration under the resonant vibration characteristics experienced at this over-speed point. By removing material from the crankshaft and by providing greater radii at the edges, this cracking was eliminated even though the actual twisting of the crankshaft was probably increased. Also, during the development of the engine, it was noticed that the front intermediate main bearing was subjected to frequent, unexplained failures on the test stand. It was further found that this failure could be induced by one of two methods, either reducing main oil pressure below 75 lbs. or introducing air into the oil pump inlet, a condition prevalent in a large number of aircraft not having a good oil system and means of eliminating air entrained in the oil leading to the tank from the engine. This bearing burning problem was solved in two ways. First, the passages up through the crankshaft while the engine was running and showed that for 75 lbs. main oil pressure, only 10 to 15 lbs. pressure was available for lubrication at the front intermediate main bearing.

There are two main oil supplies to the nose of the engine. One is through the crankshaft and the second is through oil passages at the top of the crankcase. However, due to the oil flow requirements of the crankshaft, oil entering the rear of the crankshaft reaches only the front intermediate main bearing and the front of the crankshaft is fed from the line traversing the upper half of the crankcases. The second cure for this bearing burning was the installation of air separators in the main journals where small holes were drilled on the exact center line or led from this center line of the crankshaft. The whirling motion of the crankshaft has a tendency to separate the oil from the air and concentrating air at the center of the crankshaft. Since it is also necessary to provide sludge traps in the crankshaft, the oil feeds from one section of the crankshaft to the other are necessarily taken as close to the center line as possible, which resulted in feeding air rather than oil. These small bleed holes offer little resistance to the air but sufficiently resist oil flow so that no detrimental pressure losses are encountered.

SCAVENGING

In plain English, it can be stated that the initial R-4360 "wouldn't scavenge nohow". At the present time, no breathing difficulties or excessive power losses up to altitudes of 40,000 feet are being experienced in any R-4360 models. We have not had any full power turbo operations at this altitude but are confident no trouble will occur. In order to obtain this scavenging efficiency, large numbers of changes were made over a period of two and one-half years. These changes involved increasing the capacity of scavenge pumps, adding stages or locations of scavenge pumps, revising the inlet conditions of scavenge pumps and the installation of screens in certain compartments to act as air separators in order to allow the oil to be reduced in volume and increased in density so that it could be efficiently handled by the scavenge pumps. The fact that this is a dry sump engine means that oil must be scooped up by the pump "on the run". During this period of scavenge testing, several rigs were made and engines were tested both on the test stand and in flight. The airplane being used was the converted F4U which, because of its high angle and high rate of climb provided the most severe scavenge conditions that could be encountered.

Whereas the addition of scavenge pumps and the increasing capacity of the present scavenge pumps all contributed greatly, the final effective scavenging was not made possible until the use of screens. (Figure 26). These screens work on the theory that all the oil in the engine is whipped to a froth similar to soap suds in the kitchen sink. When draining the sink, solid water under the soap suds will flow out of the drain. However, if this water contains enough soap content, it is possible by beating to whip it all into a froth and removal of the drain plug will have no effect on the draining of the soap suds. The same condition exists in the engine and the scavenge pumps cannot suck the oil suds as they exist in the engine. Since this oil foam is traveling at high velocity, it can be impinged upon an object such as the screen. The oil having a higher inertia than the air in it, and since a big bubble cannot pass through a small hole, the oil, by virtue of its own inertia will pass through the screen and emerge with a greatly reduced air content, thus approaching a more nearly liquid condition and being easily handled by the scavenge pumps.

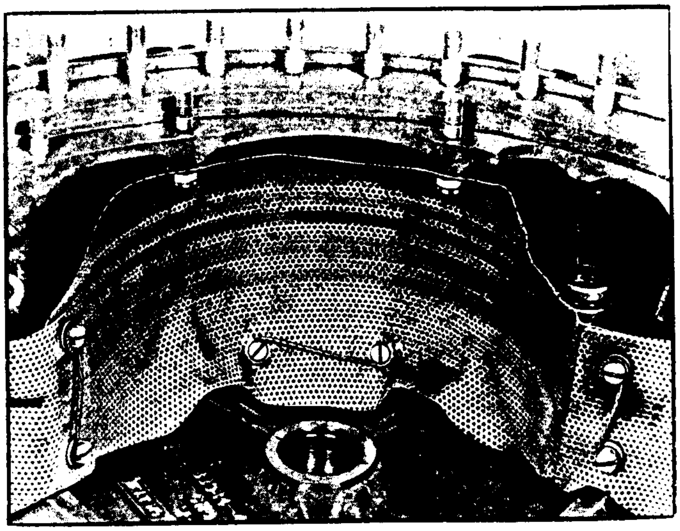

Figure 26 - The Scavenge Oil Air Separator Screen

An engine may now throw oil out the breathers, yet may not be scavenging, which will be evidenced by a high temperature rise and loss in horsepower. Initially, the R-4360 with a four-coupling variable speed supercharger drive developed around 200 less horsepower for a given manifold pressure than the same engine with a two-gear fixed supercharger drive in the same compartment. This was due to the fact that the couplings were whirling the oil around at such a rate it could not be scavenged from the compartment. Attention is directed to the blower drive compartment of the -4 engine where oil flow in this compartment is at the rate of 120 lbs. per minute, yet the volume capacity for oil in this compartment is less than 15 lbs. It is in this compartment that the screens contributed their most valuable results and reduced the horsepower losses from over 200 to less than 35.

CYLINDERS

Fortunately, no great amount of trouble has been experienced around the use of the fore and aft forged head cylinder. There were a few weaknesses which showed up such as exhaust valve guide erosion, intake valve seat warpage, exhaust rocker ear valve gear coking, and rocker cap gasket leakage. Exhaust valve guide wear was corrected by the use of steel-tipped guides for scraping lead deposits off the valve stem as shown in Figure 27. Its problem, actually, was not so much one of cylinder as it was "improvement" of fuels for a lead content increases these lead deposits in the combustion systems of an engine become more and more troublesome. Exhaust rocker ear coking was primarily caused by lack of cooling fins on that ear and very little circulation of cooling air, a condition non-existant in other Pratt and Whitney engines up to that time. The revised baffle system as shown on the -35 engine greatly helps to alleviate this condition. This, combined with an oil cooling jet in the ear and the use of silicone rocker cap gaskets have alleviated most of the troubles. The intake valve seat warpage was simply eliminated by changing from a bronze to a steel seat plus a change in seat width and valve spring action.

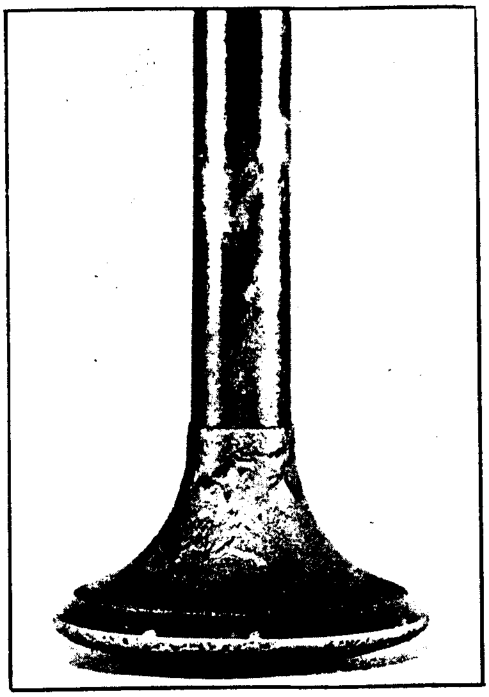

Figure 27 - Exhaust Valve Run With Stainless Steel Tipped Valve Guide For 250 Hrs. At 1820 RPM, 150 BMEP, .050 F/A Ratio

The initial baffle system in the R-4360 was such that the cooling of ignition harness, rocker ears, intake pipes, etc., was dependent upon the care the aircraft manufacturer took in providing proper exits for the hot air from the engine. Experience has indicated that the background of engine experience of people employed by the aircraft manufacturers is necessarily limited along details such as this and it is far better insurance for us to completely enclose the engine so as to control these operating conditions. Further, the use of the -35 type of hooded baffle has greatly reduced temperatures in these parts by enclosing them in the cold air side of the cooling system, which has resulted in considerably longer life of the parts.

INTAKE PIPES

On the R-4360, the intake pipe is in a much larger radius on the engine than on other models. The cylinders in themselves are very flexible and under high power operation do considerable weaving, resulting in considerable stresses being imposed on the intake pipe. It became necessary to instigate very wide gaps between the pipes on adjacent cylinders in order to allow sufficient flexibility without pipe strain. Whereas this was successful in reducing the pipe failures, serious epidemics of coupling failures of the hose connection type resulted from this action. A successful solution to this bursting caused by backfires was accompanied by installing a metal shield supported by a bulge in the coupling. However, these rubber hoses were still subject to deterioration and development was continued to find an all-metal coupling which would be satisfactory in this application. After considerable experimenting, a metal coupling was developed.

Another problem encountered by the intake pipes being at a larger radius was the matter of fuel and oil drainage from the lower intake pipes. Since the intake pipe is considerably lower than the intake valve, pulling the engine through does not insure against hydraulicing, as a very large reservoir of gasoline can be accumulated in the lower part of the intake pipe. The engine can be run at low speeds with this collection in the pipe. When the throttle is advanced and the air velocity within the intake pipe increases, a sudden wave of this liquid will develop and will generally be forced into the front bank cylinder which results in wrecking the engine. To eliminate this, automatic drains were installed in the lower intake pipes which would close whenever a differential air pressure in either direction was imposed upon it. Since relatively small force was available to operate these valves, they had to be light, consequently, they were not too durable, particularly under conditions which promoted backfires and could stick very easily by gum or dust. Since, for normal periods of shutdown, oil is not generally known to leak past pistons and into cylinders in a degree sufficient to cause hydraulicing, and since most hydraulicing is the result of improper use of the automatic mixture control in starting, it was felt that if we could trap the fuel in the blower before it got to the intake pipe, the danger of hydraulicing could be eliminated.

To take care of engines which had been left in storage for any length of time, small plugs were provided in the lower pipe for hand drainage, but for day to day operation an annulus around the intake pipe as it left the blower leading to a chamber with a float valve was quite satisfactory in removing fuel in a liquid state tending to flow to the lower pipes from the blower. Of course, our operating instructions specify that an engine should be started on the prime and that the mixture control should not be moved out of idle cut-off until the engine starts to fire. With the new blower rim priming on the R-4360, this is a very easy and simple way to start. However, there are, unfortunately, a large number of people schooled in the theory that the only way to start an engine is to jockey the mixture control.

If, on the R-4360, 15 pounds of boost pressure were supplied during starting and the mixture control and the throttle were moved to the full open positions which has been known to happen among some of the very careless personnel, it would require a hole 1 1/8 inches in diameter in the intake pipe to drain off the fuel so as to prevent hydraulicing. This not only results in a prohibitive size hole but may result in serious fire hazard should torching of the exhaust system set off this fuel which is pouring to the ground or the deck of an aircraft carrier. In the space allowed with the float type drain valve, we have been unable to get a valve of sufficient size to take care of more than 75% of this requirement. However, we feel that the extreme case is so unusual and rare that its probability of happening is very remote.

IGNITION SYSTEM

The use of seven 4-cylinder dual magnetos on the R-4360 was prompted for reasons of simplicity, durability, and continued reliability of the engine should enemy action damage one or two of the magnetos. These parts on the engine have been relatively little source of trouble. Considerable controversy, however, has been waged over the mertis of a single-piece molded and sealed ignition harness vs. detachable lead and also reversible units.